

SUPPLEMENTARY DATA TO THE ARTICLE

Integrating uncertainty of preferences and predictions in decision models: an application to regional wastewater planning

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SI-1. Case information

Table SI 1: Overview of the four involved wastewater treatment systems and their characteristics. The organizations' names are anonymized. WWTP: wastewater treatment plant; COD-PE: population equivalent based on a specific chemical oxygen demand of 120 gO₂d⁻¹Person⁻¹; CHPP: combined heat and power plant.

Characteristic	BB	AZ	NW	GM
Average load 2013-2016 (COD-PE)	14097	63247	9000	17529
Design size (COD-PE)	22500	75800	12000	23500
Projected design size 2040 (COD-PE)	22000	104000	15000	26000
Hydraulic dimensioning (L/s)	320	660	180	320
First construction	1975	2003	1975	1979
Last rehabilitation measures	2008	-	2016	2010
Phosphate precipitation	yes	yes	no	yes
Sludge utilization	Digestion; biogas used for CHPP. Digested sludge transported for dewatering.	Dewatering of sludge.	Digestion with co-substrates; biogas used for district heating. Dewatering of digested sludge	Digestion; biogas used for CHPP. Dewatering of digested sludge
The dewatered sludge of all four WWTPs is finally transported to a different site and incinerated.				

Table SI 2: Alternatives that were initially discussed but not included in the set of modeled alternatives.

Alternative	Description
4C	Wastewater that arrives at WWTP BB and at WWTP NW will be pumped to WWTP AZ; these three systems and organizations will be merged. WWTP BB will be decommissioned. WWTP GM remains independent. Sewage from the merged WWTP will be transported (via a pipeline or trucks) to WWTP NW for digestion and biogas production. Digester supernatant will be returned or a treatment for the supernatant will be built at WWTP NW.
5B	A completely new modular treatment plant will be built at a new site. All other WWTP will be decommissioned. Potentially, further WWTP in addition to the four WWTP in this study could merge.
6	According to the topography, at different points in the sewer network the wastewater of the catchment of WWTP BB will be rerouted to the sewer networks of WWTP NW, WWTP AZ, and a further WWTP. WWTP BB will be decommissioned.
7	A higher dilution of wastewater in the stream NZ will be achieved by rerouting a second stream into stream NZ and by routing non-polluted parasitic water directly into stream NZ. Due to the higher dilution, the negative ecological effects are mitigated and the WWTP BB would not fall under the legal criteria for WWTP that have to take measures against micropollutants.
8	Decentralization of wastewater treatment. Waste- and stormwater will be treated at the source, in a decentralized fashion and/or locally infiltrated. WWTP BB will be decommissioned.

SI-2. Predictions

Table SI 3: Attributes, their range from worst to best considered level, how their levels were predicted, and how uncertainty distributions for the levels were obtained. For the dimensioning of the wastewater treatment plants (WWTPs) for 2040, the same technical standard and an increase in 20% for the load was assumed (Table SI 1). The hydraulic dimensioning was assumed constant. PE: population equivalent; Nm³: normal cubic meter.

Attribute [Unit]	Range	Prediction	Uncertainty
Annual cost in 2040 [mio. CHF/year]	12.1 to 6.3 mio. CHF/year	<p>In a static cost assessment, the overall costs can be expressed as yearly costs for the entire system. Calculation of yearly costs by the engineering office according to a cantonal directive. In this static comparison, yearly costs in the region in 2040 were estimated as the sum of operation costs, depreciation costs (based on replacement values of the infrastructures), and costs for interest (based on changes in replacement values). Assumption about service life: WWTP 33 years, sewers 80 years, pumps 50 years.</p> <p>Infrastructures such as sewers that do not change in any alternative were not included. Subsidies were not considered.</p>	<p>Assumption of normal distributions with mean: point estimate by the engineering office; and standard deviation: $\frac{1}{4}$ of the outcome range of alternatives from a sensitivity analysis by the office.</p>
Ecological state of river NZ as given by the Swiss modular stream assessment [points]	40 to 75 points	<p>This attribute is based on a method for stream assessment in Switzerland (MSK, http://www.modul-stufen-konzept.ch/index_EN) that is routinely used to evaluate the ecological state of rivers. Changes in the ecological state of river NZ were estimated based on monitoring data for sites above and below the WWTP for 2011 (diatoms, macroinvertebrates), 2011–2012 (nutrients), and estimates by the research team where no data was available (fish, physical state, micropollutants). The variation of the attributes across samplings is reduced by choosing an adequate time of the year for sampling and avoiding sampling times immediately after storm events. The assessment then leads to the typical ecological state at each site. We used the package <i>ecoval</i> to assess individual modules (Schuwirth et al. 2017). To aggregate the individual modules, an aggregation model of four experts has been elicited and used as described in Haag et al. (2019a).</p>	<p>Monitoring data and estimates were considered uncertain and this uncertainty propagated to the assessment. For chemical parameters, these uncertainty distributions were estimated based on data, otherwise assumptions of distributions by the research team. The expert aggregation was averaged over the four experts. Fitting of normal distributions to the uncertain assessment outcomes.</p>
Population for which micropollutants will be removed [number of people]	0 to 104000 people	<p>Assuming that treatment systems have a similar performance, for the environment, a small total discharge of micropollutants is relevant, i.e., pollutants coming from a large population are removed. Based on number of people connected to the WWTP in 2016. A population growth factor with $\mathcal{N}(1.1, 0.05)$ truncated to [1, 1.25] was assumed. The micropollutants for the whole population that is connected to a WWTP with micropollutant treatment would be removed.</p>	<p>Forward propagation of uncertainty in population growth. Fitting of normal distributions to the outcomes.</p>

Attribute [Unit]	Range	Prediction	Uncertainty
Nu Number of buildings of WWTPs higher than 10m [buildings] Short: buildings	8 to 1 buildings	High buildings can impact the amenity of the landscape. In the case study area this has been an issue with residents before. Current number of buildings taken from cadaster data. Estimates for the number of buildings required for new infrastructure and buildings that could be demolished by research team.	Different possibilities to build new infrastructure lead to different possible numbers of buildings for some alternatives. Modeled by uniform distributions over the possible numbers.
Number of protected areas that could be impaired [areas impaired] Short: protected_areas	3 to 0 areas	Extensions of WWTPs or other new buildings can impact protected zones, even though this might be legally allowed. Estimation by engineering office based on cadaster data on protected areas and possible new buildings.	For some areas it is uncertain if there will be an impact or not. This is, modeled by uniform distributions over the possible numbers.
Gross electrical energy required [MWh/year] Short: electricity	8000 to 3220 MWh/year	The gross electricity demand gives an indication how energy-intensive a system is. Calculation by a simple model. Total gross electrical energy is the sum of energy for WWTP operation, pumping, and micropollutant removal (where applicable), across the region. Current electricity consumption for operation of WWTP (per PE) given by monitoring data. Energy for treatment of new WWTP estimated based on literature values. For energy demand in 2040 a growth factor with $\mathcal{N}(1.10, 0.05)$ truncated to [1,125] for the PE was included. Energy for pumping estimated by engineering office. Energy for micropollutant treatment estimated based on literature values and number of PE. Gross electrical energy does not consider that some energy can be recovered in WWTP, e.g., by a combined heat and power plant.	Estimation of the uncertainty ranges for parameters by research team and assumption of uniform distributions. Forward propagation of all uncertainties. Fitting of normal distributions to the outcomes.
Production of biogas from sludge [thous. Nm3/year] S Short: biogas	128 to 2180 thous. Nm3/year	The production of biogas is an important way to make the energy in sludge available. Calculation by a simple model. Current production (per PE) given by monitoring data. Estimation of production in new WWTP based on literature values. For gas production in 2040 a growth factor with $\mathcal{N}(1.10, 0.05)$ truncated to [1,125] for the PE was included. This attribute only partly covers the objective "High utilization of energy in sludge". Biogas production also requires energy and is only useful if the gas can be efficiently used. Energy can also be recovered by burning dewatered sludge. In addition, the transport or processing of sludge can decrease the net energy benefit.	Estimation of the uncertainty ranges of production per PE by research team and assumption of uniform distributions. Forward propagation of all uncertainties. Fitting of normal distributions to the outcomes.
Land requirements for infrastructure [m2] [m2] Short: land_consumption	56000 to 32000 m2	The land consumption can be expressed as the footprint of the infrastructures on the ground. Estimation by engineering office based on current situation and typical land requirements for the infrastructures.	Assumption of normal distributions with standard deviation: 5% of mean value.

Attribute [Unit]	Range	Prediction	Uncertainty
Jobs in the wastewater sector in the region [full time equivalents] Short: jobs	6 to 13 FTE	The available jobs can be expressed as full time equivalents needed for the operation of the system. Estimation by engineering office based on current situation.	If there are several possible outcomes, this was modeled by uniform distributions over the possible outcomes.
Number of municipalities in the largest organizational unit in the region [municipalities] Short: organization_size	52 to 18 municipalities	When there are more municipalities in an organization, there might be less possibility for influence for individual municipalities. The form of the organization (e.g., public association, cooperation, ...) will also influence the possibility for co-determination of municipalities. This is not captured by the attribute. The prediction are directly given by the number of municipalities in current organizations.	None.
Number of residents in 1 km radius around WWTPs that will possibly be negatively affected by a system change [residents] Short: residents	0 to 2500 residents	The more people in the perimeter of a WWTP the higher are the chances that some are negatively affected. Current population in the impacted area estimated based on population density map. To calculate population in 2040 inclusion of a growth factor with $\mathcal{N}(1.1,0.05)$ truncated to [1,125]. Assumption that small changes to current WWTPs would not affect the population. For a newly built WWTP (alternative 5) a possible location was assumed, but higher uncertainty in the growth factor $\mathcal{N}(1,0.2)$ truncated to [-0.5,1.25].	Density ranges in map assumed to be bounds of uniform distributions. Propagation of uncertainty in this data and in the growth factor. Fitting of normal distributions to the outcomes.
Estimate of long-term suitability of the alternative on a four point scale Short: long_term [points]	1 to 4 points	The long-term nature of a solution is difficult to capture, which is why we used a constructed attribute. 1: short term solution, 4: optimum in the long term. Starting with four points, points were subtracted for each of the following conditions that applied to an alternative: (1) wastewater discharge into a small stream, (2) no micropollutant removal for large WWTP, (3) no sludge digestion for large WWTP.	Two future scenarios considered: a) Strict: conditions 1-3 apply b) Tolerant: condition 1 applies Modeling via an uniform distribution over the possible outcomes.
Number of further alternatives that remain feasible once the alternative has been realized Short: open_paths [paths]	0 to 4 paths	Flexibility can be defined in different terms. Here we were interested in the feasible possibilities for change that remained after implementing an alternative. The number of feasible paths is given by the definition of alternatives. Due to the long life-spans of infrastructures configurations cannot easily be changed once they are built.	None.
Local production of biogas from sludge at WWTP NW [thous. Nm³/year] biogas_dist_heat	0 to 560 thous. Nm ³ /year	The local biogas production can be directly used in the district heating. Calculation by a simple model. Current production (per PE) given by monitoring data. Estimation of production after mergers were based on estimated PE and assumption about production per PE. Due to co-digestion of other wastes in the reactor, the gas production based only on sludge is difficult to estimate. For gas production in 2040 a growth factor with $\mathcal{N}(1.1,0.05)$ truncated to [1,125] for the PE was included.	Estimation of the uncertainty ranges of production per PE by research team and assumption of uniform distributions. Forward propagation of all uncertainties. Fitting of normal distributions to the outcomes.

Table SI 4: Predictions and uncertainty distributions for the attributes (see Table SI 2 for explanations) and alternatives (Table 3, main text). \mathcal{N} : normal distribution (mean and standard deviation in parentheses); U: uniform distribution (min and max in parentheses).

Attribute	0	1A	1B	2	3A	3B	4Aa	4Ab	4Ba	4Bb	5
cost	$\mathcal{N}(945,0.65)$	$\mathcal{N}(10,0.63)$	$\mathcal{N}(9.5,0.65)$	$\mathcal{N}(9.4,0.63)$	$\mathcal{N}(8.5,0.58)$	$\mathcal{N}(9.5,0.63)$	$\mathcal{N}(7.8,0.53)$	$\mathcal{N}(9.6,0.43)$	$\mathcal{N}(8.8,0.63)$	$\mathcal{N}(10.6,0.5)$	$\mathcal{N}(9.6,0.45)$
ecol_state	$\mathcal{N}(50,3.2)$	$\mathcal{N}(63,3.4)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$	$\mathcal{N}(67,3.5)$
micropol	0	$\mathcal{N}(17000,720)$	0	0	0	0	0	$\mathcal{N}(72000,3030)$	0	$\mathcal{N}(72000,3030)$	$\mathcal{N}(86000,3660)$
buildings	6	$U(7,6)$	6	$U(6,5)$	5	$U(7,5)$	$U(5,3)$	$U(6,4)$	$U(6,4)$	$U(7,4)$	$U(4,2)$
protected_areas	0	0	1	$U(1,2)$	2	3	$U(1,2)$	$U(1,2)$	$U(2,3)$	$U(2,3)$	$U(0,3)$
electricity	$\mathcal{N}(3800,249)$	$\mathcal{N}(3890,251)$	$\mathcal{N}(3800,249)$	$\mathcal{N}(4140,348)$	$\mathcal{N}(4760,645)$	$\mathcal{N}(4760,645)$	$\mathcal{N}(4650,713)$	$\mathcal{N}(5220,725)$	$\mathcal{N}(4650,713)$	$\mathcal{N}(5220,725)$	$\mathcal{N}(5550,707)$
biogas	$\mathcal{N}(619,41)$	$\mathcal{N}(619,41)$	$\mathcal{N}(619,41)$	$\mathcal{N}(623,54)$	$\mathcal{N}(417,31)$	$\mathcal{N}(1612,210)$	$\mathcal{N}(164,18)$	$\mathcal{N}(164,18)$	$\mathcal{N}(1501,231)$	$\mathcal{N}(1501,231)$	$\mathcal{N}(1604,273)$
land_consumption	$\mathcal{N}(52000,1300)$	$\mathcal{N}(53000,1330)$	$\mathcal{N}(52000,1300)$	$\mathcal{N}(47000,1180)$	$\mathcal{N}(44000,1100)$	$\mathcal{N}(48000,1200)$	$\mathcal{N}(36000,900)$	$\mathcal{N}(38000,950)$	$\mathcal{N}(40000,1000)$	$\mathcal{N}(42000,1050)$	$\mathcal{N}(34000,850)$
jobs	$U(10,12)$	$U(11,13)$	$U(10,12)$	$U(8,10)$	$U(8,10)$	$U(9,11)$	$U(6,8)$	$U(7,9)$	$U(7,9)$	$U(8,10)$	$U(6,8)$
organization_size	18	18	18	22	31	31	40	40	40	40	52
residents	0	0	0	$\mathcal{N}(600,90)$	0	$\mathcal{N}(1900,290)$	$\mathcal{N}(1900,290)$	$\mathcal{N}(1900,290)$	$\mathcal{N}(1900,290)$	$\mathcal{N}(1900,290)$	$\mathcal{N}(1700,370)$
long_term	$U(1,3)$	$U(1,3)$	$U(2,4)$	$U(2,4)$	$U(2,4)$	$U(3,4)$	$U(2,4)$	$U(3,4)$	$U(1,4)$	4	4
open_paths	4	0	4	0	2	2	1	1	1	1	0
biogas_dist_heat	$\mathcal{N}(253,23)$	$\mathcal{N}(253,23)$	$\mathcal{N}(253,23)$	$\mathcal{N}(458,48)$	$\mathcal{N}(253,23)$	$\mathcal{N}(253,23)$	0	0	0	0	0

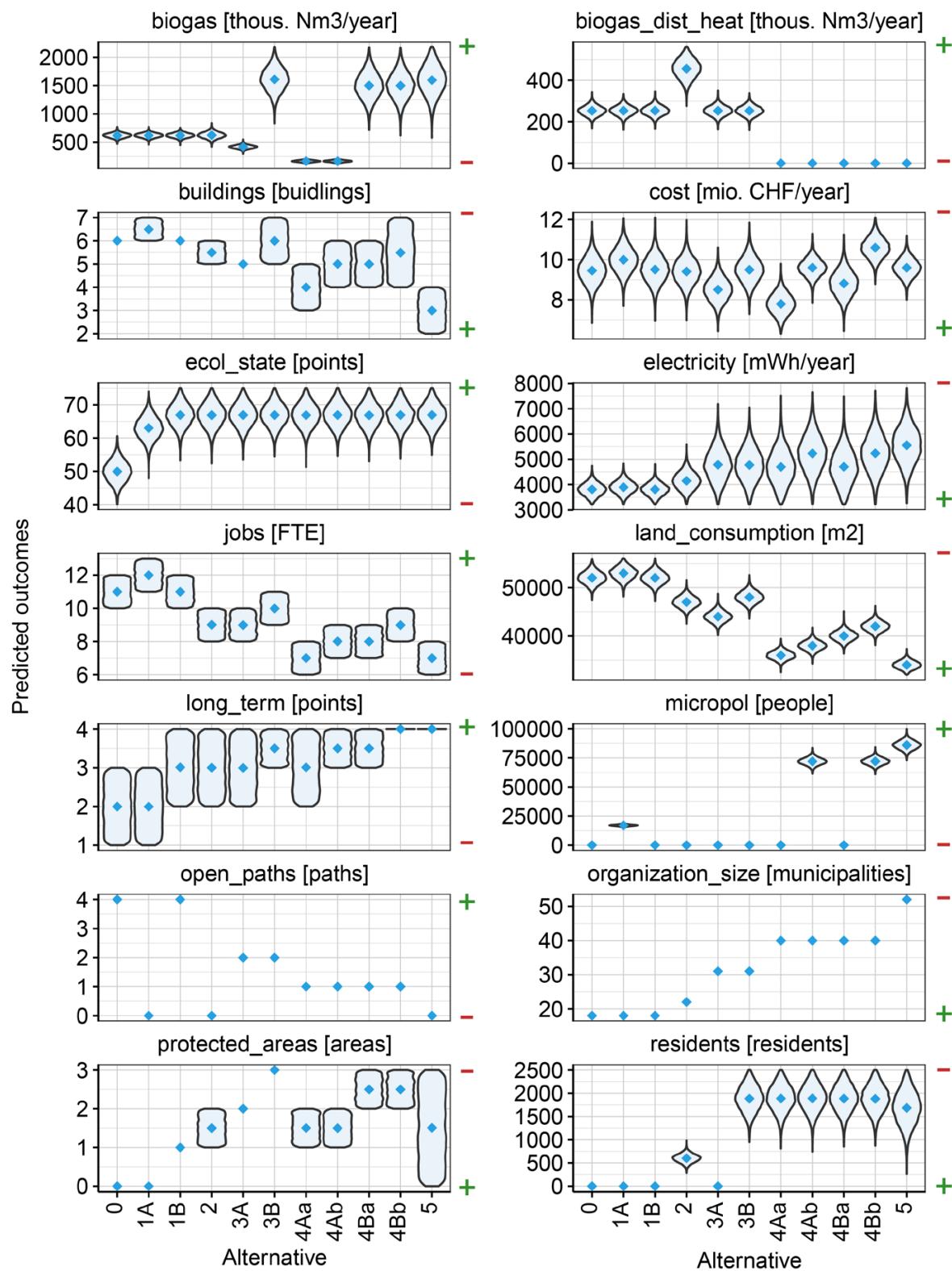


Figure SI 1: Blue diamonds indicate the expected values of predictions (y-axis) of the alternatives (x-axis; Table 3 in main text) for different attributes (Table SI 3). The violin plots show the mirrored probability density of these predictions. The signs + and - on the right y-axis indicate the best and worst attribute level that was considered. Table SI 4 gives an overview over the underlying probability distributions. Predictions were based on Monte Carlo simulation with 10000 samples. See Table SI 3 for details how predictions were obtained.

SI-3. Preference information

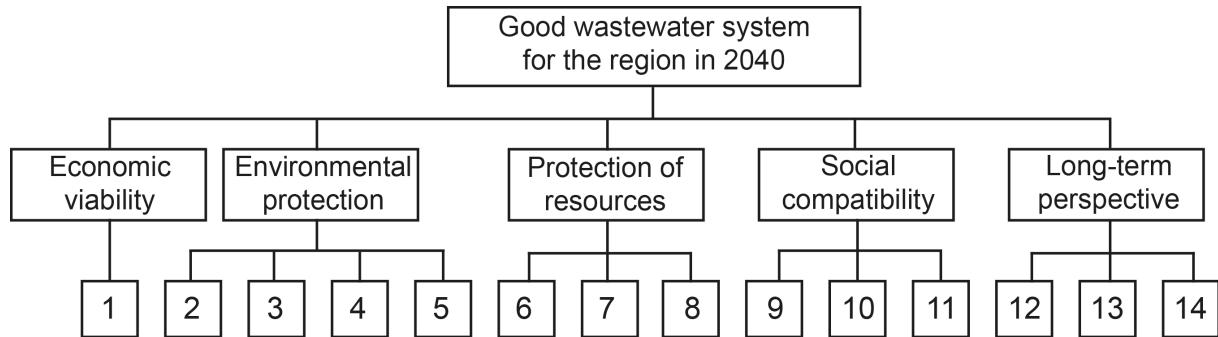


Figure SI 2: Hierarchical structure of the preference model. For details on objectives see Table 2, main text.

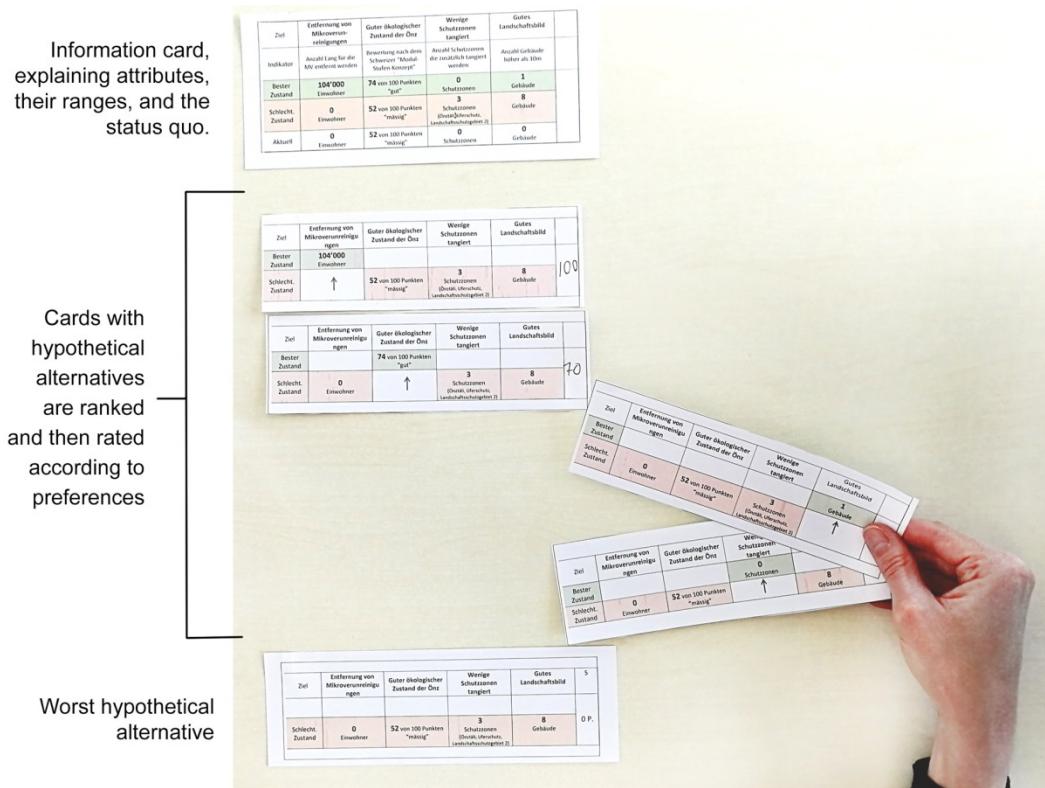


Figure SI 3: Elicitation of preferences using cards that can be moved around by the respondent. Here: the Swing procedure to elicit weights (Eisenführ et al. 2010): The worst hypothetical alternative at the bottom shows all the objectives that are considered at this step (in this example four objectives) to be at their worst level in this decision situation; it receives 0 points. The hypothetical alternatives, each with one of the objective at its best level for the decision situation, are first ordered by the respondent according to preferences, with decreasing importance from top to bottom. The best hypothetical alternative at the top receives 100 points. The respondent then assigns points to the other hypothetical alternatives according to the preferences. The weights are obtained by normalization. Single-attribute value functions and certainty equivalents were also elicited with such a card-based approach.

Table SI 5: Elicited preferences given by the stakeholders (SH; Table 1, main text) about different objectives (Table 2, main text). These were used as input to the modeling. $v(x)$: value of attribute x given by value function (VF). CE: certainty equivalent. $u(CE)$: utility of certainty equivalent given by utility function. Swing was conducted in each branch separately (comparison 1) and then across branches (comparison2) with one objective out of each branch.

SH	Higher level objective	Objective	Lowest-level value function shape	Midpoint x of VF: $v(x)=0.5$	Weights: Swing points comparison 1	Weights: Swing points comparison 2	Certainty equi- valent. $u(CE)=0.5$	Adjustm. factor for weights ^d
NW	Economic viability	cost	linear	9.2	1	0.1	10.7	1
	Environmental protection	ecology_nz ^a	convex	61 ^b	1	1	52.7 ^c	1.42
		micropollutants	linear	52000	0.9			1
		protected_areas		0.6				1
		landscape		0.3				1
	Protection of resources	electricity ^a	linear	5610 ^b	0.8			1
		sludge_utilization	linear	1150	1	0.3		1
		land_consump.		0.4				1
	Social compatibility	jobs	linear	9.5	1	0.5		1
		co_determination		0.7				1
GM	Residents ^a	residents ^a	linear	1250 ^b	0.9			1.09
	Long-term perspective	long_term		0.3				1
		flexibility		1				1
		district_heating ^a	convex	345 ^a	1	0.9		1.12
	Economic viability	cost	concave	9.8	1	0.8	8.6	1
		ecology_nz ^a	concave	53 ^b	0.7			1.95
	Environmental protection	micropollutants	convex	60000	1	0.75	40000	1
		protected_areas		0.68 (0.65–0.7)				1
		landscape		0.2				1
	Protection of resources	electricity ^a	concave	5700 ^b	0.55			1
BB		sludge_utilization	concave	800	1	1		1
		land_consump.		0.25				1
	Social compatibility	jobs		0.7				1
		co_determination	concave		1	0.7		1
	Residents ^a	residents ^a		0.2				1.14
	Long-term perspective	long_term	concave	2	0.7			1
		flexibility	concave		1	0.5		1
		district_heating ^a		0.2				1.13
	Economic viability	cost	linear	9.2	1	0.9	10.4	1
	Environmental protection	ecology_nz ^a	sigmoid ^e	60 ^e	0.75			1.23
BB		micropollutants	concave	40000	1	0.9		1
		protected_areas		0.5				1
		landscape		0.4				1
	Protection of resources	electricity ^a		0.55 (0.5–0.6)				1
		sludge_utilization	linear	1150	1	0.725 (0.7–0.75)		1
Social compatibility		land_consump.		0.8				1
	Jobs	jobs		0.2				1
		co_determination		0.4				1
Residents ^a	Residents ^a	residents ^a		1	0.725 (0.7–0.75)			1.14

SH	Higher level objective	Objective	Lowest-level value function shape	Midpoint x of VF: v(x)=0.5	Weights: Swing points comparison 1	Weights: Swing points comparison 2	Certainty equivalent. u(CE)=0.5	Adjustm. factor for weights ^d
Long-term perspective	long_term			0.9				
	flexibility			1	1			1
	district_heating ^a	concave		0.5				1.13
Economic viability	cost	linear ^e	9.2 ^e	1	0.8	10.4		1
Environmental protection	ecology_nz ^a	sigmoid ^e	60 ^e	1	1			1.23
	micropollutants			0.5				1
	protected_areas			0.35				1
Protection of resources	landscape			0.2				1
	electricity ^a			2 ^f (1-3)	0.25			1
	sludge_utilization			1.5 ^f (1-3)				1
Social compatibility	land_consump.			1 ^f				1
	jobs			0.25 (0.2-0.3)				1
	co_determination			0.075 (0.05-0.1)				1
Long-term perspective	residents ^a			1	0.2			1.14
	long_term			1				1
	flexibility			1	0.5			1
	district_heating ^a			0.1				1.13

a For this value function, the underlying attribute range increased after the elicitation

b The elicited $v(x) = 0.5$ point was transformed to the new range and is given here. We transformed the original point x_{old} by using the formula $x_{new} = \frac{x_{new}^+ - x_{new}^-}{x_{old}^+ - x_{old}^-} (x_{old} - x_{old}^+) + x_{new}^+$ with x^+ : worst level of range, x^- : best level of range. This linear transformation assumes the same general shape of the new and the old value functions. This linear extension is the simplest assumption. We did not have information to justify that a more sophisticated assumption would be sensible.

c The elicited CE point was transformed to the new range and is given here. We transformed it by using the formula above.

d To account for the increased attribute range after elicitation, weights were multiplied by this adjustment factor before normalization. The adjustment factor is the proportion of the new value function range (which is one) covered by the old attribute range (cf. Eisenföhr et al. 2010). adj. fac. = $\frac{1}{v_{new}(x_{old}^+) - v_{new}(x_{old}^-)}$. We did not have

information to justify a more sophisticated assumption. The uncertainty in the value functions leads to a distribution of these adjustment factors; we used the expected value (mean) of that distribution.

e Not formally elicited, but interpretation of discussion with interviewee(s).

f The stakeholder felt unable to allocate points to these comparisons, but only gave a general ranking. To the stakeholder the allocation of points would depend on the net energy balance not the gross balance. We represented this statement by a high uncertainty of the point allocation. Because the comparison at the upper level was done with the last ranked objectives, this objective received 1 at the local level and the points of the others are greater than 1.

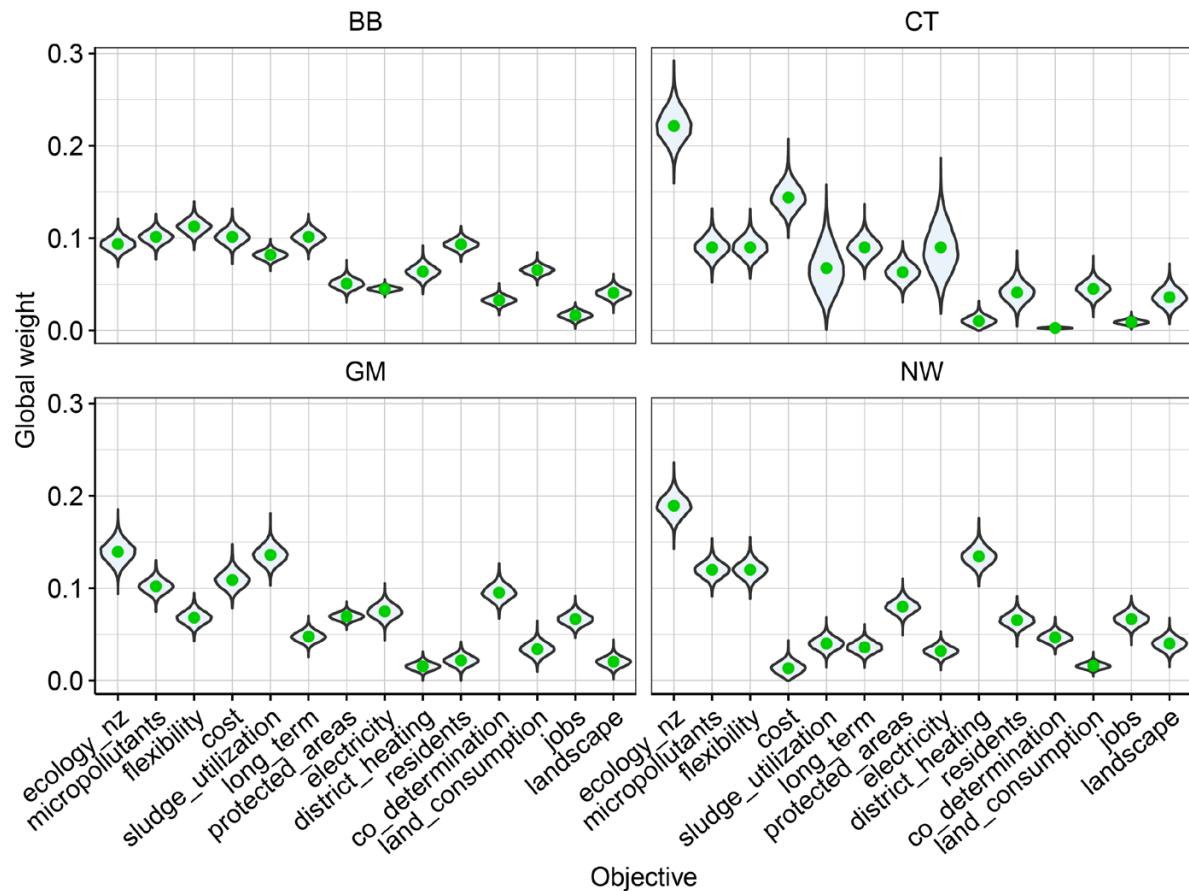


Figure SI 4: Visualization of the global weights of the four interviewed stakeholders (CT, BB, GM, NW; Table 1 main text), estimated based on the information in Table SI 5 and the assumptions about uncertainty in these statements detailed in the main text (section 3.3.3). Global weights are the weights at the lowest level of the objectives hierarchy; added together, they sum up to one. Violin plots show the mirrored probability density of the weights, the green dots indicate the global weight obtained if we ignore uncertainty in statements.

Table SI 6: Risk attitude parameter r estimated from the statements on the certainty equivalents in Table SI 5, given uncertainty in the value functions. The value functions can be converted to utility functions using Equation 7 (main text) and this parameter.

interviewee	attribute	mean r	min r	max r
CT	cost	1.89	1.06	2.91
BB	cost	1.89	1.06	2.91
GM	cost	-1.82	-2.84	-0.96
GM	micropollutants	1.67	0.84	2.65
NW	cost	2.58	1.65	3.77
NW	ecology_no	2.14	1.23	3.23

SI-4. Comparison of EEU with other measures of overall performance

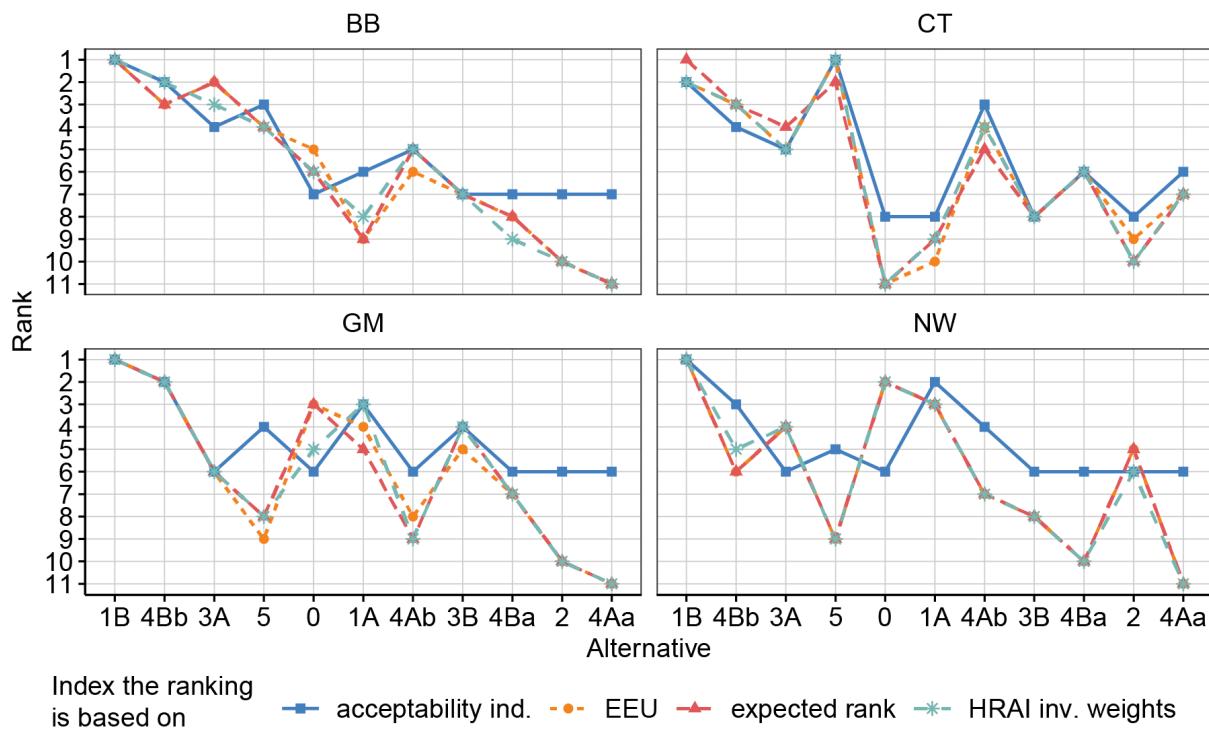


Figure SI 5: Overall ranking of alternatives based on different measures of overall performance, given uncertain predictions and preferences, which lead to different rankings in each simulation run. Acceptability ind.: acceptability index of stochastic multicriteria acceptability analysis (SMAA) (Lahdelma et al. 1998). The index measures the frequency with which an alternative obtains first rank given the uncertainties. The ranking orders alternatives by decreasing frequency of obtaining the first rank. EEU: expected expected utility; the ranking is based on decreasing EEU. Expected rank: arithmetic mean of rank distributions; the ranking orders alternatives by decreasing expected rank. HRAI inv. weights: Holistic rank acceptability index with inverse weights (Tervonen and Figueira 2008). This index is based on the frequency with which alternatives receive each rank; these frequencies are aggregated by a weighted sum with weights: 1/rank number (see Tervonen and Figueira 2008).

SI-5. Sensitivity to simplifying assumptions about preferences

Table SI 7: Expected expected utility (EEU) and rank of the alternatives (Table 3, main text) when different levels of detail in preferences are used, i.e., different assumptions (see Table 5, main text). Results for the four stakeholders (CT, BB, GM, and NW, Table 1 main text)

Assumption in analysis	Alternative	BB		CT		GM		NW	
		EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
1. Uncertain distributions	0	0.65	5	0.59	11	0.72	3	0.66	2
	1A	0.6	9	0.62	10	0.72	4	0.64	3
	1B	0.72	1	0.73	2	0.76	1	0.73	1
	2	0.59	10	0.62	9	0.67	10	0.6	5
	3A	0.69	2	0.7	5	0.71	6	0.63	4
	3B	0.64	7	0.65	8	0.72	5	0.57	8
	4Aa	0.57	11	0.66	7	0.62	11	0.44	11
	4Ab	0.65	6	0.71	4	0.69	8	0.58	7
	4Ba	0.61	8	0.67	6	0.71	7	0.46	10
	4Bb	0.68	3	0.71	3	0.76	2	0.59	6
	5	0.66	4	0.74	1	0.69	9	0.55	9
2. Linear lowest-level value functions	0	0.67	3	0.64	9	0.68	4	0.69	2
	1A	0.6	9	0.63	11	0.68	3	0.67	3
	1B	0.73	1	0.74	2	0.73	1	0.75	1
	2	0.6	8	0.64	10	0.63	10	0.62	5
	3A	0.68	2	0.71	5	0.64	7	0.66	4
	3B	0.63	6	0.66	8	0.66	6	0.6	7
	4Aa	0.55	11	0.67	7	0.55	11	0.46	11
	4Ab	0.63	7	0.72	4	0.63	8	0.6	8
	4Ba	0.59	10	0.68	6	0.63	9	0.48	10
	4Bb	0.66	5	0.73	3	0.7	2	0.6	6
	5	0.66	4	0.75	1	0.66	5	0.56	9
3. Precise weights	0	0.65	5	0.59	11	0.72	3	0.66	2
	1A	0.6	9	0.62	10	0.72	4	0.64	3
	1B	0.72	1	0.73	2	0.76	1	0.73	1
	2	0.59	10	0.62	9	0.67	10	0.6	5
	3A	0.69	2	0.7	5	0.71	6	0.63	4
	3B	0.64	7	0.65	8	0.72	5	0.57	8
	4Aa	0.57	11	0.66	7	0.62	11	0.44	11
	4Ab	0.65	6	0.71	4	0.69	8	0.58	7
	4Ba	0.61	8	0.67	6	0.71	7	0.46	10
	4Bb	0.68	3	0.71	3	0.76	2	0.59	6
	5	0.66	4	0.74	1	0.69	9	0.55	9
4. Ranking weights	0	0.55	7	0.57	11	0.68	9	0.6	6
	1A	0.54	8	0.66	6	0.74	3	0.66	2
	1B	0.63	4	0.72	3	0.75	2	0.69	1
	2	0.43	11	0.64	9	0.68	10	0.62	3
	3A	0.58	5	0.66	5	0.69	8	0.62	4

Assumption in analysis	Alternative	BB		CT		GM		NW	
		EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
5. Additive model	3B	0.56	6	0.64	8	0.72	5	0.59	7
	4Aa	0.48	10	0.62	10	0.6	11	0.44	11
	4Ab	0.71	2	0.7	4	0.71	7	0.57	9
	4Ba	0.53	9	0.65	7	0.71	6	0.47	10
	4Bb	0.75	1	0.72	2	0.8	1	0.6	5
	5	0.7	3	0.74	1	0.73	4	0.58	8
	0	0.72	5	0.67	11	0.78	4	0.73	2
	1A	0.67	10	0.69	10	0.77	5	0.71	3
	1B	0.78	1	0.79	2	0.81	1	0.79	1
	2	0.68	9	0.71	9	0.75	9	0.7	4
	3A	0.75	2	0.75	3	0.76	7	0.69	5
	3B	0.71	7	0.72	8	0.79	3	0.65	9
	4Aa	0.67	11	0.74	6	0.71	11	0.56	11
	4Ab	0.71	6	0.75	5	0.74	10	0.65	8
6. Risk neutrality	4Ba	0.69	8	0.74	7	0.77	6	0.57	10
	4Bb	0.74	4	0.75	4	0.79	2	0.66	6
	5	0.75	3	0.79	1	0.76	8	0.65	7
	0	0.43	5	0.37	11	0.51	3	0.44	2
	1A	0.38	9	0.4	10	0.51	4	0.42	3
	1B	0.5	1	0.52	2	0.56	1	0.51	1
	2	0.36	10	0.4	9	0.45	10	0.37	5
	3A	0.48	2	0.48	5	0.49	6	0.41	4
	3B	0.42	7	0.43	8	0.5	5	0.35	8
	4Aa	0.35	11	0.44	7	0.39	11	0.25	11
	4Ab	0.43	6	0.49	4	0.47	8	0.36	7
	4Ba	0.38	8	0.45	6	0.49	7	0.26	10
	4Bb	0.46	3	0.5	3	0.55	2	0.37	6
	5	0.44	4	0.53	1	0.47	9	0.33	9
7. All simplifi- cations	0	0.52	3	0.48	10	0.52	2	0.54	2
	1A	0.44	9	0.47	11	0.52	3	0.52	3
	1B	0.58	1	0.59	2	0.58	1	0.62	1
	2	0.47	6	0.49	9	0.48	7	0.5	4
	3A	0.52	4	0.54	3	0.47	8	0.5	5
	3B	0.46	7	0.51	8	0.5	6	0.45	6
	4Aa	0.42	11	0.53	7	0.41	11	0.35	11
	4Ab	0.46	8	0.54	5	0.45	10	0.43	9
	4Ba	0.44	10	0.53	6	0.47	9	0.35	10
	4Bb	0.48	5	0.54	4	0.51	5	0.44	8
	5	0.53	2	0.6	1	0.52	4	0.45	7

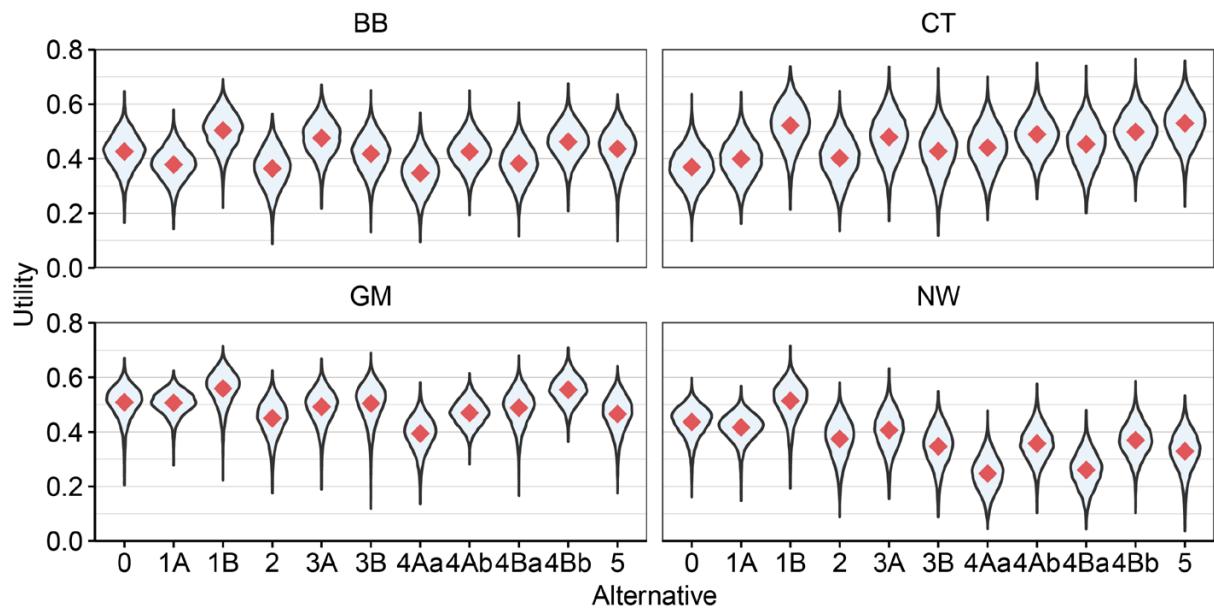


Figure SI 6: Results for the preference models assuming risk neutrality of stakeholders. Violin plots show the mirrored probability density of overall utilities (y-axis) of the alternatives (x-axis; Table 3, main text) for four stakeholders (CT, BB, GM, and NW, Table 1 main text). Diamonds indicate the expected expected utility (Table SI 7). Uncertainties in attribute outcomes, lowest-level value functions, weights, and aggregation parameter γ were propagated.

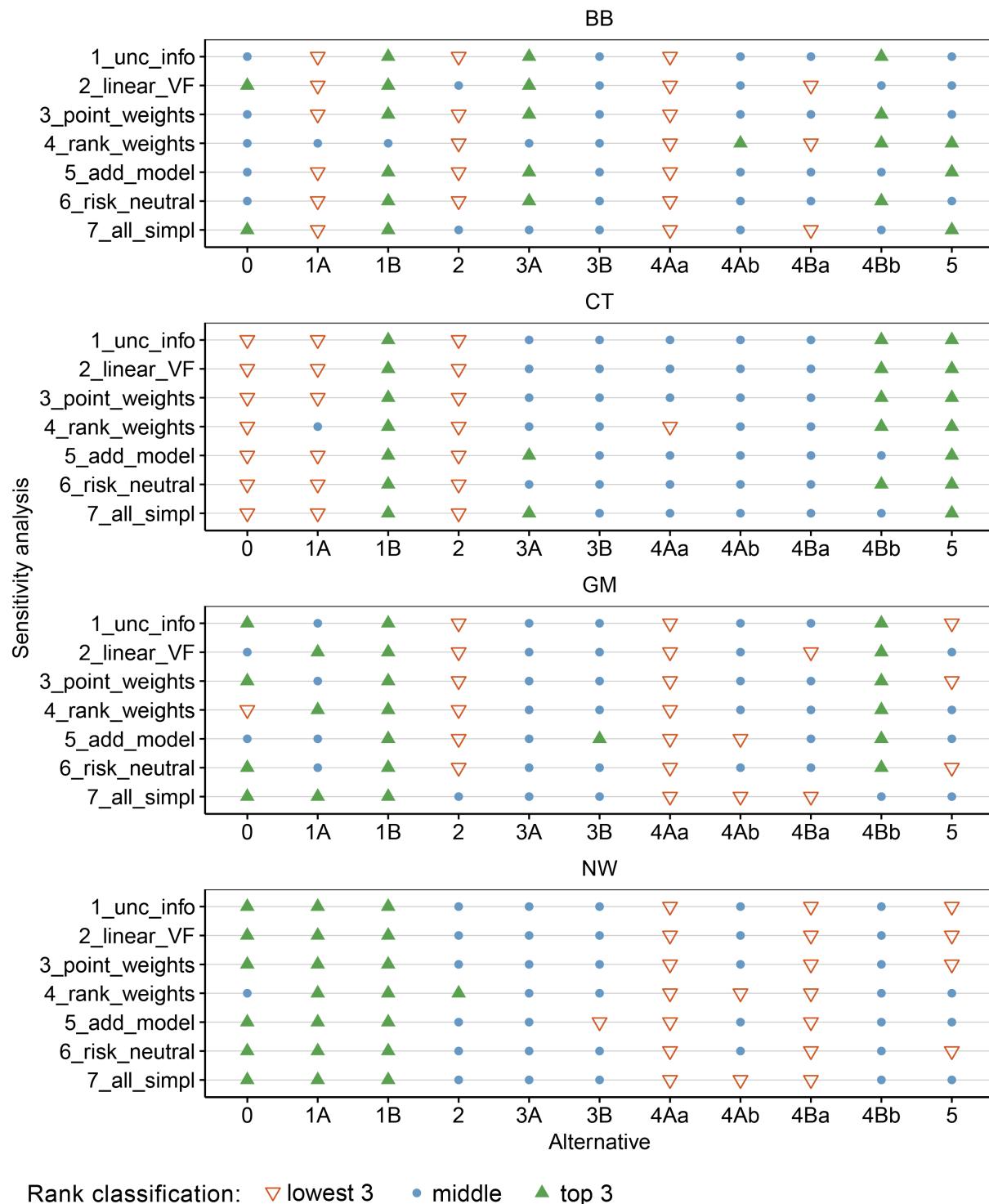


Figure SI 7: Rank classification of alternatives (x-axis; Table 3, main text) when different distributions of preference parameters are used (y-axis; section 3.4.2, main text). The three highest-ranked alternatives are indicated by a green triangle, the three worst-ranked alternatives by a red triangle, and the five alternatives in the middle by a blue circle. The ranks are based on the expected expected utilities of the alternatives (Table SI 7). Each panel shows the results for one of the four stakeholders (CT, BB, GM, NW; Table 1, main text).

SI-6. Sensitivity to hierarchical structures

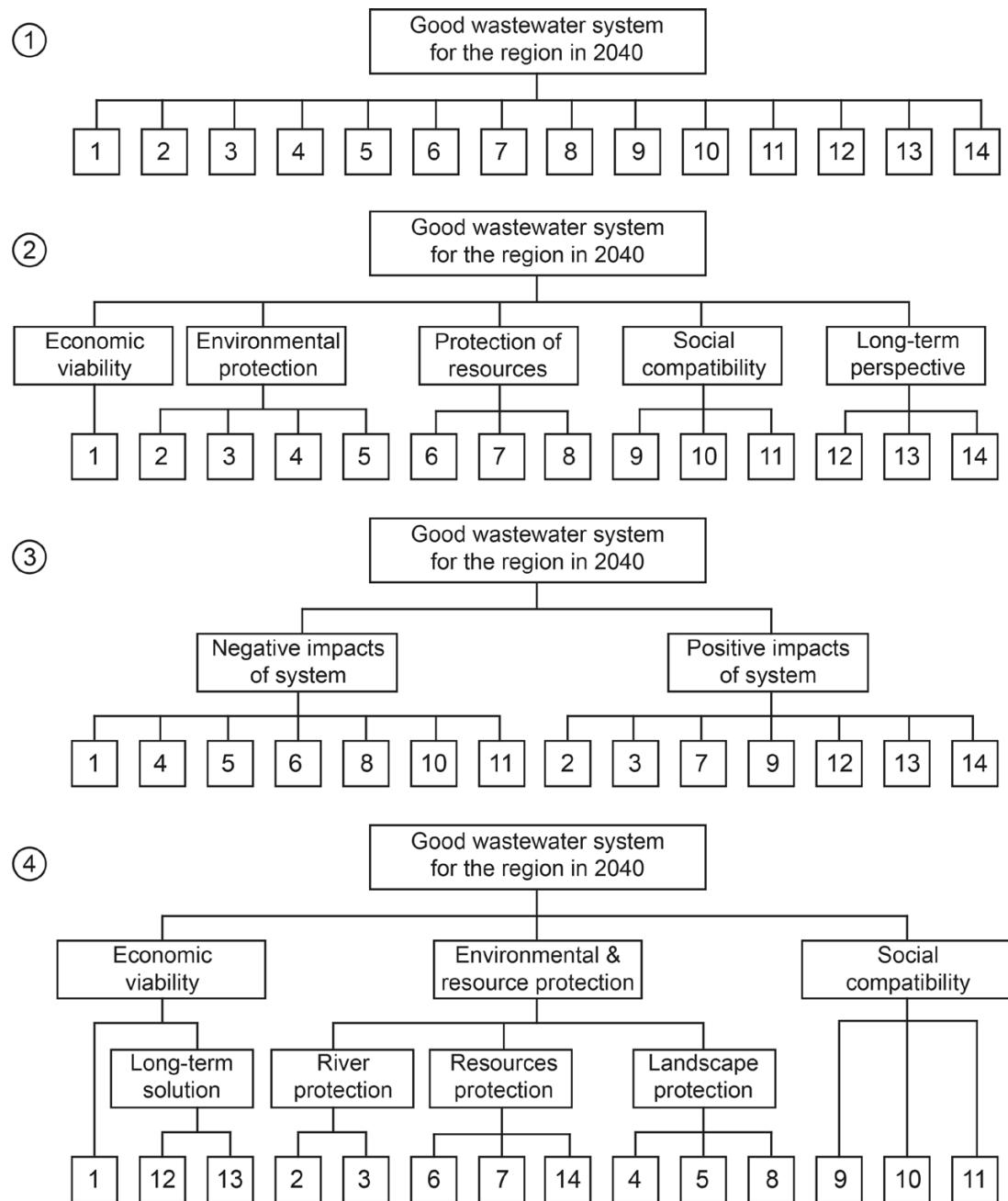


Figure SI 8: Four different possibilities for hierarchical structures based on the same 14 objectives (Table 2, main text). For an analysis of the sensitivity of the results to these different hierarchies see Table SI 8 and Figure SI 9.

Table SI 8: Expected expected utility (EEU) and resulting ranks of alternatives (Table 3, main text) for preference models using different hierarchical structures (Figure SI 8). Only results for stakeholder GM (Table 1, main text) are shown. The results are illustrated in Figure SI 9.

Alternative	Structure 1		Structure 2		Structure 3		Structure 4	
	EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
0	0.72	3	0.73	3	0.72	3	0.73	3
1A	0.72	4	0.73	4	0.72	4	0.72	4
1B	0.75	1	0.75	1	0.75	1	0.76	1
2	0.65	9	0.66	9	0.66	9	0.66	10
3A	0.69	5	0.7	6	0.69	5	0.7	6
3B	0.69	6	0.7	5	0.69	6	0.7	5
4Aa	0.6	11	0.6	11	0.61	11	0.61	11
4Ab	0.67	8	0.67	8	0.67	8	0.68	8
4Ba	0.68	7	0.69	7	0.68	7	0.69	7
4Bb	0.74	2	0.74	2	0.74	2	0.74	2
5	0.65	10	0.66	10	0.65	10	0.66	9

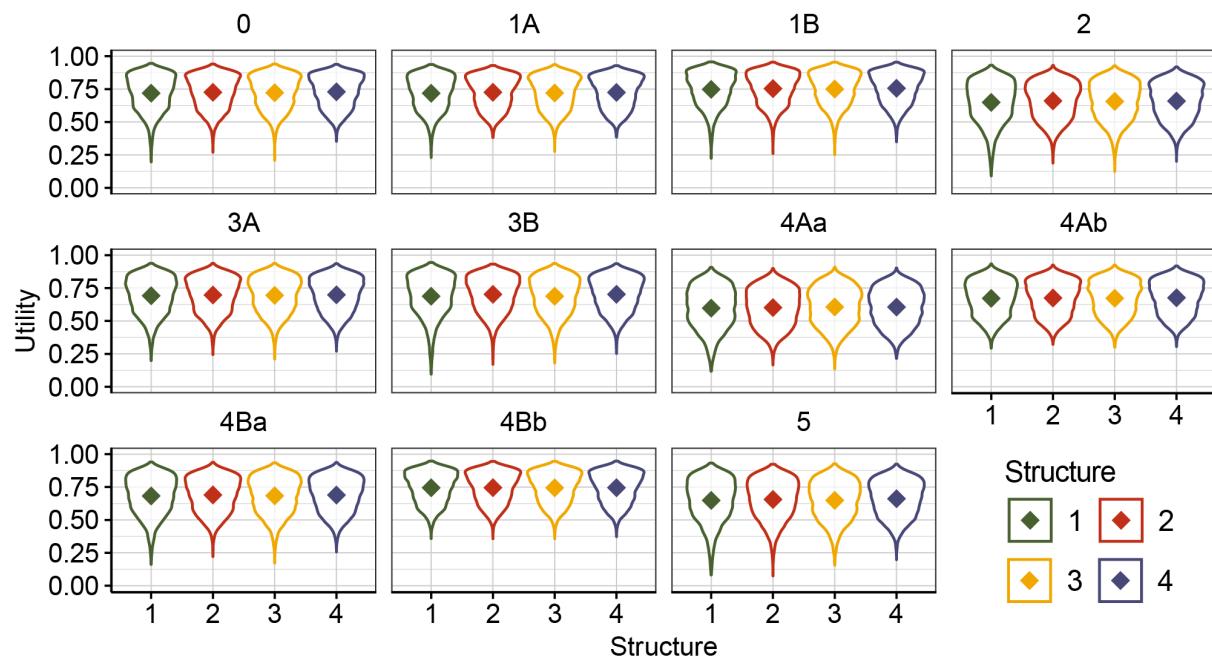


Figure SI 9: Results for an analysis using four different hierarchical structures (x-axis, Figure SI 8) of the preference model. Violin plots show the mirrored density of overall utilities (y-axis) of the alternatives (Table 3, main text). Only results for stakeholder GM (see Table 1, main text) are shown. Diamonds indicate the expected expected utility of the alternatives. The numerical values are given in Table SI 8. Uncertainties in attribute outcomes, lowest-level value functions, weights, aggregation parameter γ , and risk attitude were propagated (“uncertain distributions”, Table 5, main text).

SI-7. Sensitivity to leaving out objectives

Table SI 9: Expected expected utility (EEU) and resulting ranks of alternatives (Table 3, main text) for preference models leaving out each one of the 14 objectives (Table 2, main text) in turn, but retaining the other 13 objectives. “None” denotes the full model, including all 14 objectives. We show results for each of the four stakeholders: CT, BB, GM, NW (Table 1, main text).

Objective left out	Alternative	BB		CT		GM		NW	
		EEU	Ran k						
None	0	0.65	5	0.59	11	0.72	3	0.66	2
	1A	0.6	9	0.62	10	0.72	4	0.64	3
	1B	0.72	1	0.73	2	0.76	1	0.72	1
	2	0.58	10	0.62	9	0.67	10	0.59	5
	3A	0.69	2	0.69	5	0.71	6	0.63	4
	3B	0.64	7	0.64	8	0.71	5	0.56	8
	4Aa	0.56	11	0.66	7	0.61	11	0.44	11
	4Ab	0.65	6	0.7	4	0.69	8	0.58	7
	4Ba	0.6	8	0.67	6	0.7	7	0.46	10
	4Bb	0.68	3	0.71	3	0.76	2	0.59	6
co_determination	5	0.66	4	0.74	1	0.68	9	0.54	9
	0	0.63	7	0.59	11	0.68	6	0.64	2
	1A	0.58	9	0.62	10	0.68	7	0.62	4
	1B	0.7	1	0.73	2	0.73	3	0.71	1
	2	0.57	10	0.62	9	0.63	10	0.57	8
	3A	0.69	2	0.69	5	0.68	8	0.62	3
	3B	0.63	6	0.65	8	0.69	5	0.55	9
	4Aa	0.56	11	0.66	7	0.59	11	0.44	11
	4Ab	0.65	5	0.7	4	0.68	9	0.58	6
	4Ba	0.6	8	0.67	6	0.69	4	0.46	10
cost	4Bb	0.68	3	0.71	3	0.75	2	0.59	5
	5	0.68	4	0.74	1	0.75	1	0.58	7
	0	0.64	6	0.57	11	0.72	4	0.66	2
	1A	0.6	8	0.63	8	0.73	3	0.64	3
	1B	0.72	1	0.74	3	0.76	2	0.73	1
	2	0.57	10	0.61	10	0.66	10	0.59	5
	3A	0.68	3	0.67	5	0.69	7	0.63	4
	3B	0.63	7	0.64	7	0.71	5	0.56	8
	4Aa	0.52	11	0.61	9	0.57	11	0.43	11
	4Ab	0.65	5	0.71	4	0.68	8	0.58	7
district_heating	4Ba	0.58	9	0.65	6	0.69	6	0.46	10
	4Bb	0.7	2	0.75	2	0.78	1	0.59	6
	5	0.66	4	0.75	1	0.68	9	0.54	9
	0	0.65	7	0.59	11	0.72	4	0.67	4
	1A	0.6	10	0.62	10	0.72	3	0.65	5
	1B	0.72	2	0.73	2	0.76	2	0.75	1
	2	0.56	11	0.62	9	0.67	10	0.55	9
3A	3A	0.7	5	0.7	5	0.71	7	0.64	6

Objective left out	Alternative	BB		CT		GM		NW	
		EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
ecology_nz	3B	0.64	8	0.65	8	0.72	5	0.57	8
	4Aa	0.61	9	0.67	7	0.63	11	0.53	11
	4Ab	0.7	4	0.71	4	0.7	8	0.68	3
	4Ba	0.65	6	0.68	6	0.72	6	0.55	10
	4Bb	0.73	1	0.72	3	0.77	1	0.69	2
	5	0.7	3	0.74	1	0.69	9	0.63	7
	0	0.68	2	0.68	3	0.74	1	0.71	1
	1A	0.58	8	0.57	10	0.69	4	0.61	3
	1B	0.7	1	0.69	1	0.73	2	0.7	2
	2	0.55	10	0.54	11	0.62	10	0.53	5
electricity	3A	0.67	3	0.64	6	0.67	6	0.57	4
	3B	0.61	7	0.57	9	0.68	5	0.49	8
	4Aa	0.53	11	0.59	8	0.56	11	0.34	11
	4Ab	0.62	6	0.64	5	0.64	8	0.5	7
	4Ba	0.57	9	0.6	7	0.66	7	0.36	10
	4Bb	0.66	4	0.65	4	0.73	3	0.52	6
	5	0.63	5	0.69	2	0.64	9	0.46	9
	0	0.63	6	0.55	11	0.7	5	0.65	2
	1A	0.58	9	0.59	10	0.7	4	0.63	3
	1B	0.7	1	0.71	3	0.74	2	0.72	1
flexibility	2	0.57	10	0.59	9	0.65	10	0.58	6
	3A	0.69	2	0.68	5	0.7	6	0.62	4
	3B	0.63	7	0.63	8	0.71	3	0.56	8
	4Aa	0.55	11	0.64	7	0.6	11	0.43	11
	4Ab	0.64	5	0.7	4	0.68	8	0.57	7
	4Ba	0.59	8	0.66	6	0.69	7	0.45	10
	4Bb	0.68	3	0.71	2	0.76	1	0.59	5
	5	0.66	4	0.74	1	0.68	9	0.54	9
	0	0.59	10	0.53	11	0.7	8	0.6	7
	1A	0.68	2	0.69	8	0.77	1	0.73	1
jobs	1B	0.67	4	0.7	4	0.74	3	0.68	3
	2	0.67	5	0.69	7	0.72	5	0.69	2
	3A	0.67	6	0.7	5	0.69	9	0.62	5
	3B	0.6	8	0.64	10	0.7	7	0.55	9
	4Aa	0.55	11	0.68	9	0.61	11	0.45	11
	4Ab	0.64	7	0.73	3	0.69	10	0.6	8
	4Ba	0.59	9	0.69	6	0.71	6	0.47	10
	4Bb	0.68	3	0.73	2	0.76	2	0.61	6
	5	0.74	1	0.8	1	0.73	4	0.62	4
	0	0.64	6	0.59	11	0.71	5	0.64	2
jobs	1A	0.59	9	0.62	10	0.7	8	0.61	4
	1B	0.71	1	0.73	2	0.76	2	0.72	1
	2	0.58	10	0.62	9	0.67	10	0.59	5
	3A	0.69	2	0.69	5	0.71	6	0.63	3

Objective left out	Alternative	BB		CT		GM		NW	
		EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
land_consumption	3B	0.64	7	0.64	8	0.71	4	0.55	9
	4Aa	0.57	11	0.66	7	0.64	11	0.46	11
	4Ab	0.65	5	0.7	4	0.7	9	0.58	7
	4Ba	0.6	8	0.67	6	0.72	3	0.46	10
	4Bb	0.68	3	0.71	3	0.77	1	0.59	6
	5	0.66	4	0.74	1	0.71	7	0.56	8
	0	0.67	4	0.6	11	0.73	4	0.66	2
	1A	0.62	8	0.64	9	0.73	3	0.65	3
	1B	0.74	1	0.75	1	0.77	1	0.73	1
	2	0.58	10	0.62	10	0.67	9	0.6	5
landscape	3A	0.69	2	0.7	5	0.71	6	0.63	4
	3B	0.65	5	0.65	7	0.72	5	0.57	8
	4Aa	0.54	11	0.65	8	0.61	11	0.44	11
	4Ab	0.63	6	0.7	4	0.68	8	0.57	7
	4Ba	0.59	9	0.66	6	0.7	7	0.46	10
	4Bb	0.68	3	0.71	3	0.76	2	0.59	6
	5	0.63	7	0.73	2	0.67	10	0.54	9
	0	0.65	4	0.59	11	0.73	4	0.67	2
	1A	0.61	8	0.63	9	0.73	3	0.65	3
	1B	0.73	1	0.74	1	0.77	1	0.74	1
long_term	2	0.59	10	0.63	10	0.67	10	0.6	5
	3A	0.7	2	0.7	5	0.71	6	0.63	4
	3B	0.65	7	0.65	8	0.72	5	0.57	8
	4Aa	0.56	11	0.66	7	0.62	11	0.43	11
	4Ab	0.65	5	0.71	4	0.69	8	0.58	7
	4Ba	0.6	9	0.67	6	0.71	7	0.46	10
	4Bb	0.69	3	0.72	3	0.76	2	0.6	6
	5	0.65	6	0.73	2	0.68	9	0.53	9
	0	0.66	3	0.6	11	0.72	3	0.66	2
	1A	0.61	6	0.63	8	0.72	4	0.64	3
micropollutants	1B	0.7	1	0.72	1	0.75	1	0.72	1
	2	0.56	10	0.61	10	0.66	9	0.59	5
	3A	0.68	2	0.68	3	0.7	6	0.62	4
	3B	0.6	7	0.62	9	0.7	5	0.55	8
	4Aa	0.54	11	0.64	7	0.6	11	0.43	11
	4Ab	0.62	5	0.68	4	0.67	8	0.56	7
	4Ba	0.56	9	0.64	6	0.69	7	0.44	10
	4Bb	0.64	4	0.67	5	0.74	2	0.57	6
	5	0.59	8	0.69	2	0.65	10	0.49	9
	0	0.72	3	0.65	10	0.8	2	0.75	2
	1A	0.62	9	0.64	11	0.76	6	0.68	5
	1B	0.79	1	0.8	1	0.84	1	0.82	1
	2	0.66	6	0.69	8	0.75	8	0.69	4
	3A	0.77	2	0.76	2	0.79	4	0.72	3

		BB		CT		GM		NW	
Objective left out	Alternative	EEU	Rank	EEU	Rank	EEU	Rank	EEU	Rank
protected_areas	3B	0.71	4	0.71	6	0.79	3	0.65	6
	4Aa	0.64	8	0.73	4	0.69	9	0.53	10
	4Ab	0.61	11	0.69	9	0.67	10	0.53	9
	4Ba	0.68	5	0.74	3	0.78	5	0.54	8
	4Bb	0.65	7	0.7	7	0.75	7	0.55	7
	5	0.61	10	0.72	5	0.65	11	0.48	11
	0	0.62	7	0.55	11	0.70	6	0.62	3
	1A	0.57	10	0.59	10	0.70	7	0.60	6
	1B	0.71	1	0.73	3	0.76	3	0.72	1
	2	0.58	9	0.62	9	0.67	10	0.59	7
residents	3A	0.70	2	0.7	5	0.72	5	0.64	2
	3B	0.67	4	0.69	6	0.77	2	0.62	4
	4Aa	0.56	11	0.66	8	0.61	11	0.42	11
	4Ab	0.65	6	0.71	4	0.69	8	0.57	8
	4Ba	0.62	8	0.69	7	0.73	4	0.47	10
	4Bb	0.7	3	0.73	2	0.79	1	0.61	5
	5	0.66	5	0.74	1	0.69	9	0.54	9
	0	0.6	8	0.57	11	0.71	4	0.63	2
	1A	0.54	11	0.6	10	0.71	5	0.61	3
	1B	0.68	2	0.71	3	0.75	2	0.7	1
	2	0.55	10	0.61	9	0.67	10	0.57	8
sludge_utilization	3A	0.65	6	0.68	6	0.7	7	0.59	5
	3B	0.66	5	0.65	8	0.72	3	0.57	7
	4Aa	0.58	9	0.67	7	0.62	11	0.44	11
	4Ab	0.67	4	0.71	4	0.69	8	0.59	6
	4Ba	0.62	7	0.68	5	0.71	6	0.46	10
	4Bb	0.7	1	0.72	2	0.76	1	0.6	4
	5	0.67	3	0.74	1	0.69	9	0.55	9
	0	0.66	5	0.6	11	0.74	4	0.67	2
	1A	0.61	8	0.63	10	0.73	5	0.65	3
	1B	0.74	1	0.75	1	0.78	1	0.73	1
	2	0.59	10	0.63	8	0.68	8	0.6	5
3A	3A	0.72	2	0.72	4	0.74	3	0.64	4
	3B	0.61	7	0.63	9	0.67	9	0.55	8
	4Aa	0.61	9	0.7	6	0.69	7	0.46	10
	4Ab	0.69	3	0.74	2	0.77	2	0.6	6
	4Ba	0.58	11	0.66	7	0.66	10	0.44	11
	4Bb	0.66	4	0.7	5	0.73	6	0.58	7
	5	0.63	6	0.73	3	0.63	11	0.53	9

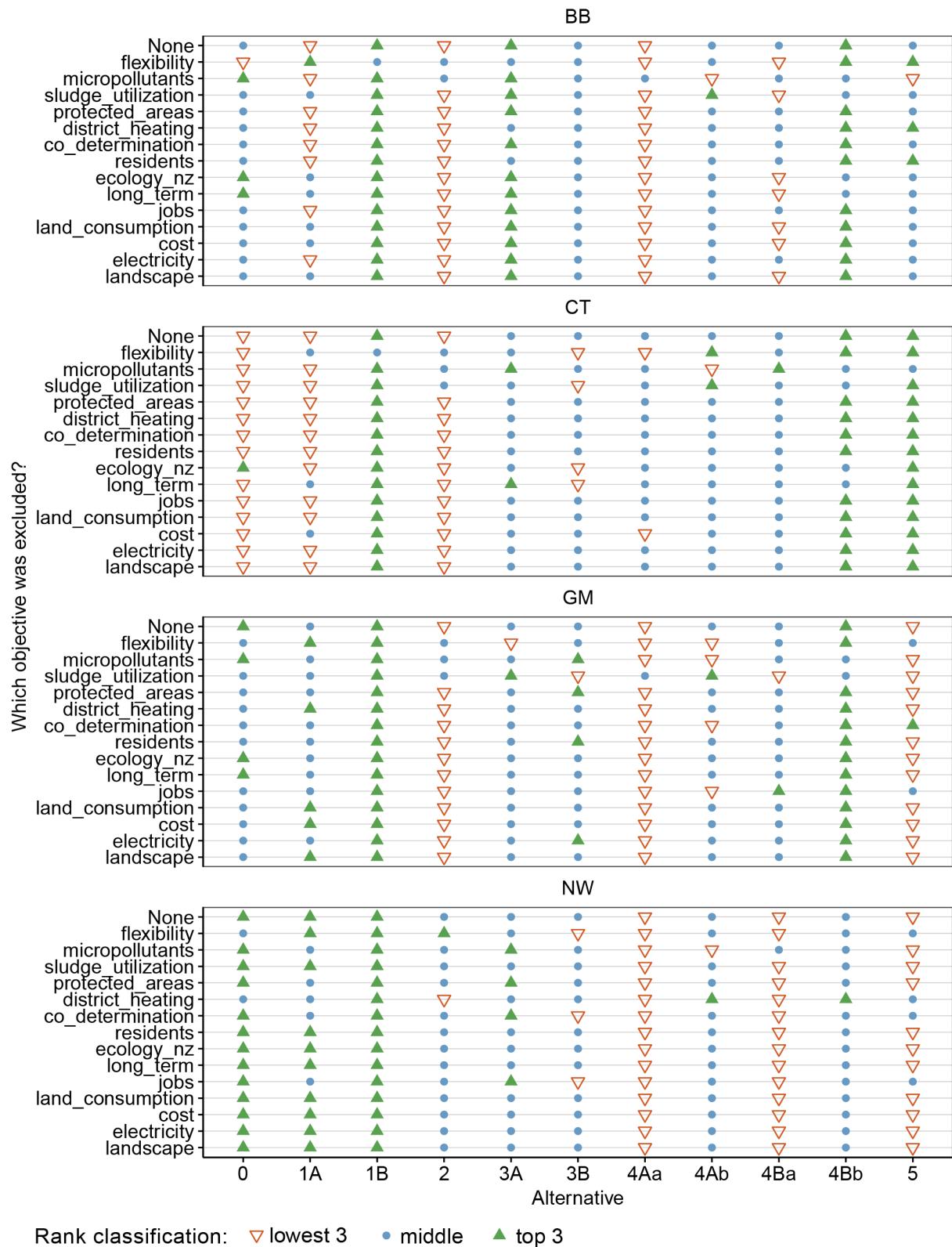


Figure SI 10: Classification of alternatives (Table 4, main text) into top, middle, and lowest based on their ranking (Table SI 9). The three highest-ranked alternatives are indicated by a green triangle, the three worst-ranked alternatives by a red triangle, and the five alternatives in the middle by a blue circle. For the analysis, objectives (Table 2, main text) were excluded one by one (y-axis) and are ordered by similarity to the case with no excluded objectives ("None"). We show the results for four stakeholders, CT, BB, GM, NW (Table 1, main text).

SI-8. Comparison to actual choices

Table SI 10: Expected expected utility (EEU) and resulting ranks of alternatives (Table 3, main text) for the reduced decision models for the four stakeholders CT, BB, GM, and NW (Table 1, main text). In the reduced models, only few objectives were considered (see section 3.5, main text for details). For stakeholder CT: cost, long_term; BB: cost, ecology_nz, sludge_utilization, flexibility; GM: cost, ecology_nz, flexibility; NW: ecology_nz, district_heating.

	BB		CT		GM		NW	
Alter-native	EEU	Rank	EEU	Rank	EEU	Rank	Rank	EEU
0	0.66	7	0.61	10	0.76	8	0.46	11
1A	0.40	11	0.55	11	0.62	11	0.68	5
1B	0.80	2	0.72	8	0.89	2	0.74	2
2	0.46	10	0.73	7	0.68	9	0.86	1
3A	0.77	4	0.80	4	0.90	1	0.74	4
3B	0.83	1	0.76	5	0.87	4	0.74	3
4Aa	0.68	6	0.85	1	0.89	3	0.47	9
4Ab	0.61	8	0.76	6	0.83	6	0.47	7
4Ba	0.80	3	0.82	2	0.86	5	0.47	10
4Bb	0.73	5	0.71	9	0.78	7	0.47	8
5	0.55	9	0.81	3	0.67	10	0.47	6

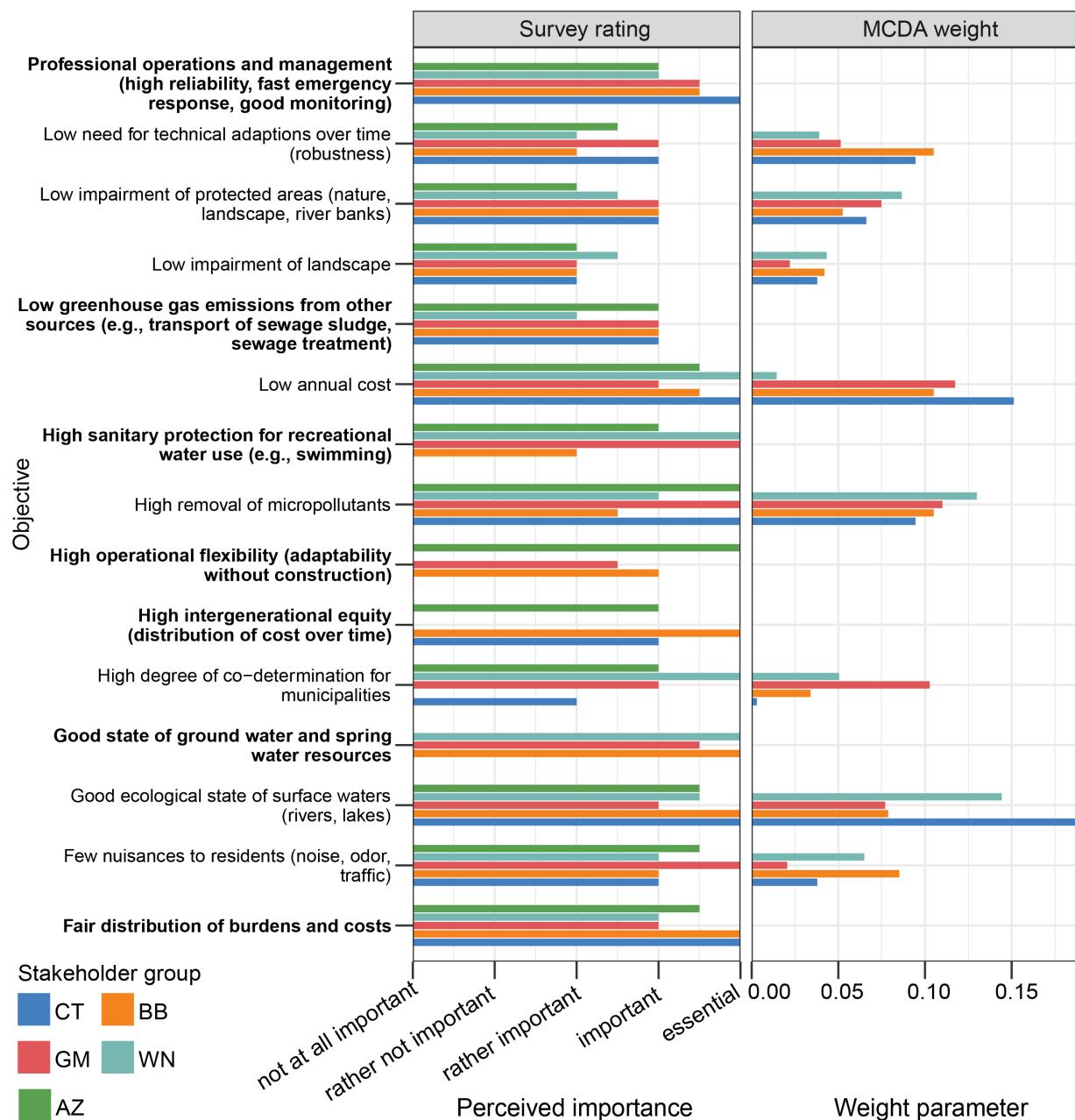


Figure SI 11: The 15 decision objectives that were considered most important in a separate online survey distributed to the stakeholders in this case study (Haag et al. 2019b). Left: average rating of perceived importance in the survey, using a Likert scale based on classes from "objective is not at all important for this decision" to "objective is essential, a decision cannot be made without it". Right: Swing weight given to an equivalent objective in the preference elicitation interview for this paper (Figure SI 6). Several objectives were not part of the full decision model used in this paper, but perceived as important in the survey (in bold). Note that the two scales have a different meaning and are only for illustration: in the survey results, the importance can be interpreted as a perceived salience. On the other hand, the weights are trade-off ratios that are relative to the magnitude of the changes.

SI-9. References

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